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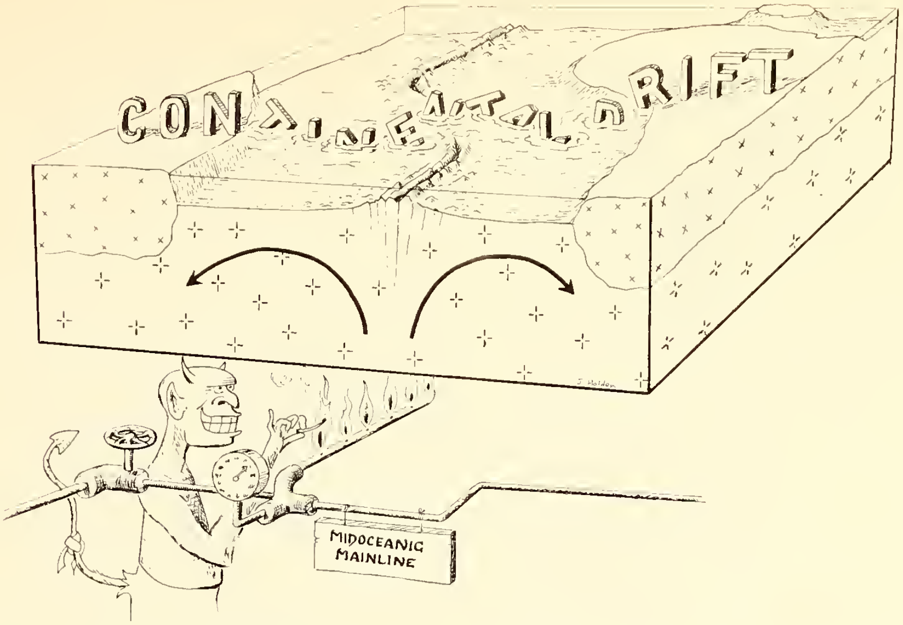

MID-OCEAN RIDGE. *Slow convection currents in the mantle below are set in motion by the internal heat of the earth. It is these currents which some believe to have caused separation of the continents, leaving the mid-ocean ridge as a "scar."*

More About Continental Drift

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(Illustrated by John Holden)

Because of readers' comments and interest in recent articles on continental drift, *Sea Frontiers* is pleased to present a fuller explanation of this controversial theory.

THESE ARE TIMES of scientific ferment. One of the great geologic debates now simmering argues the question whether the continents have been fixed in position throughout their history or whether they have drifted to their present locations. The champions of the drift theory will eventually be judged as either an *avant garde* or an idiotic fringe, depending on how the question is finally resolved. Fundamental aspects of the earth's history are involved, including the size and whereabouts of the ancient ocean

basins. So opinions are strongly opposed and statements likely to be intemperate. Reams of paper are being expended and gallons of ink spilled in this confrontation but the argument is now just warming up.

Briefly, the debate is drawn along the following lines. The continental *fixist* believes that continents and ocean basins have always remained much as we see them today, anchored in position and with but minor modifications of outline. This is the conservative philosophy and American geologists have been raised in this tradition. Continental drifters, while disagreeing among themselves as to details, believe that all the continents were once either joined together into one universal continent called Pangaea or, more likely, organized into the northern hemisphere supercontinent of Laurasia and the southern hemisphere supercontinent of Gondwana. These great landmasses then broke into pieces and drifted apart 150 to 100 million years ago. The case for Gondwana is particularly strong. It is supposed to have been a single mass incorporating the present continents of South America, Africa, Antarctica, and Australia; the subcontinents of India and Madagascar; and some "microcontinent" pieces such as the Seychelle Islands Bank and possibly the submerged Kerguelen Plateau,

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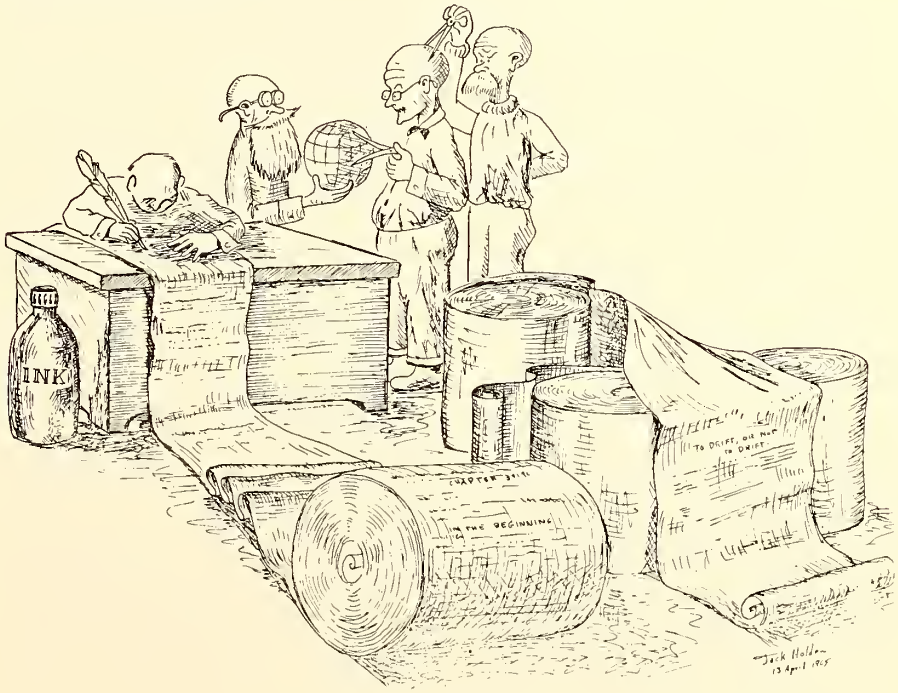


both in the Indian Ocean, and perhaps other as yet undefined pieces.

Compasses in Congealed Rocks

Interest in drift has been aroused by rock magnetism or paleomagnetic studies which offered a new and independent approach to the drift problem (See K. M. Creer, "Continents on the Move," *Sea Frontiers,* Vol. 12, No. 3, May-June, 1966). When certain rocks, having magnetic properties, as in the case of basaltic lava flows, cool from the molten state at about 575° (through the Curie point), they retain the magnetism induced in them at that time by the earth's magnetic field. Thus the crystals in them become, as it were, frozen compasses, showing the earth's magnetic orientation and magnetic dip at the time of freezing. The horizontal direction of the magnetism in the rock points in the general direction of the earth's magnetic pole, just as in the case of a compass needle. In addition, the magnetic axis of the rock crystal dips downward towards the earth's magnetic pole, being vertical in rocks near the poles and decreasing its dip towards the equator, where the axis becomes horizontal. The "rock compass" gives information as to both latitude and orientation of the rock at the time its magnetism was frozen. Yatchsmen and sailors will see that the problem of determining the original longitude of those rocks remains unsolved—precisely as with marine navigation before John Harrison invented his chronometer. Only a line-of-position is obtained, not a fix. Nevertheless, the changes in position of rocks shown by paleomagnetism provide rather convincing evidence that the continents today are not where they were 150 million years ago. In fact, most of these rock formations are *not* magnetized along the present-day direction of the earth's field, indicating they were somewhere else when they became magnetized.

Thin Ocean Floor

There are other reasons for believing that continents have been on the move. As a marine geologist, my own conversion to continental drift resulted from the numerous surprising discoveries about the sea floor. The blanket of sediment on the sea floor, if it has thickened at a rate similar to that of present day sedimentation, would have a thickness related to the length of life of the ocean floor. If the ocean floors have always existed undisturbed, there would be a very thick layer of sediment. Actually, it is surprisingly thin, indicating that the ancient ocean floor has been destroyed or reworked in some way.

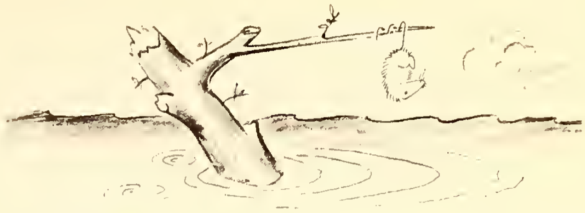
Another surprising fact is that, although the layer of granitic rock (sial) beneath the continents is very thick, it is entirely absent under nearly all of the deep sea, suggesting that the lighter granite of the continents, floating on the heavier mantle rocks below, was pulled apart when the continents separated, leaving the ocean crust bare of granite. Also, the rocks of the sea floor, as dated by their fossils or radiometrically, are surprisingly young. Further, in the absence of erosion, mountains on the sea floor should last forever as they do on the moon, but we can find no very ancient seamounts beneath the sea.

With the continental drift concept,

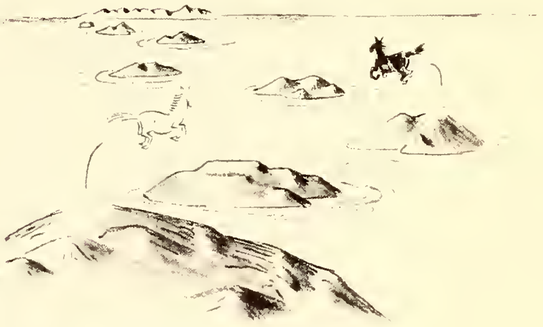
these and other surprises become the natural expectations.

Fossil Evidence

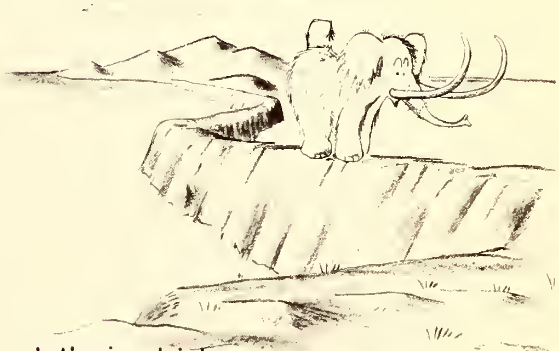
The fossils of Africa and South America indicate that, prior to 150 million years ago, the same kinds of creatures existed on both continents. Subsequently, the evolution of life had already proceeded along quite different lines on the two continents. This suggests that the continents were originally united and that free exchange of living creatures could take place, but that later they separated with both the continents and the evolution of life going their separate ways. Yet, most geologists remain skeptical of continental drift. For example, to explain this faunal dispersion most fossil experts find drift a sufficient explanation but not a necessary one. They argue, with unquestionable logic, that it is easier to drift a species than it is to drift a continent. Rafting long distances at sea upon a floating log is one mode for such dispersion, and although such rafting would be a rare event, it is argued that, over the long sweep of geologic time, anything that *might* happen *will* happen. And, also, supposedly simpler than continental



Rafting



Island Stepping Stones



Isthmian Links

Continental Drift

MOST PALEONTOLOGISTS CLAIM *that it is easier to explain the occurrence of similar species on continents widely separated by the ocean on the basis of (top) transfer of living creatures by rafting on flotsam, by easy moves along ancient island chains, or by long subsided land bridges, rather than by continental drift (bottom).*

drift, would be dispersion of living creatures over isthmian links (like the Isthmus of Panama today), which included narrow land bridges between Africa and South America, for instance.

On Continents, Ocean Basins and Icebergs

The drift concept was first formalized by the Austrian meteorologist Alfred Wegener. He made rather bold, even bizarre, assumptions about the nature of continents and ocean basins such as were required by his hypothesis. Actually, most of his suppositions have turned out to be true. We have subsequently learned that continents are not deeply rooted masses of rock but instead are separated from the earth's mantle by a sharp boundary called the Mohorovicic Discontinuity, or the Moho. We also now know that the continental blocks around most of the Atlantic and Indian Oceans have "raw edges"—mountain ranges intersect the continental margin and abruptly stop. Since World War II we have learned that the ocean floor is crustless in the sense of having no liner of continental-type granitic rock or sial. And there is no question but that continents actually float high because of their low density. Continents all in all very much resemble icebergs. The plaguing question remains: Like icebergs, do they also drift?

In our everyday experience, very large things are very hard to budge, so it defies our instincts that continents can be moved. But our instincts also deny other things—such as the entire earth moving around the sun supported by nothing at all. Galileo was forced to recant this "illogical notion" before the Inquisition, but upon leaving is said to have muttered, "Eppur si muove" ("But still it moves"). Lately the mechanical objection to drift has been removed by the suggestion that the earth's mantle undergoes a slow convection movement. In each convection cell, the mantle material, rising as a semi-liquid current in the middle, curves outwards to the sides and descends along the edges. This is the simple, well-known convection movement of water when heated in a beaker. The mantle movement sluggishly flows merely a few centimeters per year. This would be ten million times slower than the flow within the earth's molten core whose liquid turbulence accounts for the magnetic field. If such convection does occur, the continents may be entrained by the flow of the mantle and carried along as though on a conveyor belt. This would be fully analagous to the drift of icebergs which are transported, not by any inherent or impressed force, but passively by the drift of the ocean.

This mode of transport is independent of scale. A huge iceberg is moved as readily as a bergy bit. In 1927 a 10,000-square-mile iceberg, larger in area than the state of Rhode Island, drifted past the Faulkland Islands, off Argentina. So size *per se* is of no consequence. So far as the continents are concerned, we already know that subcontinental-size pieces drift. The northward motion of southern California, relative to the remainder of North America, is a case in point. It brings Los Angeles two inches closer to San Francisco every year.

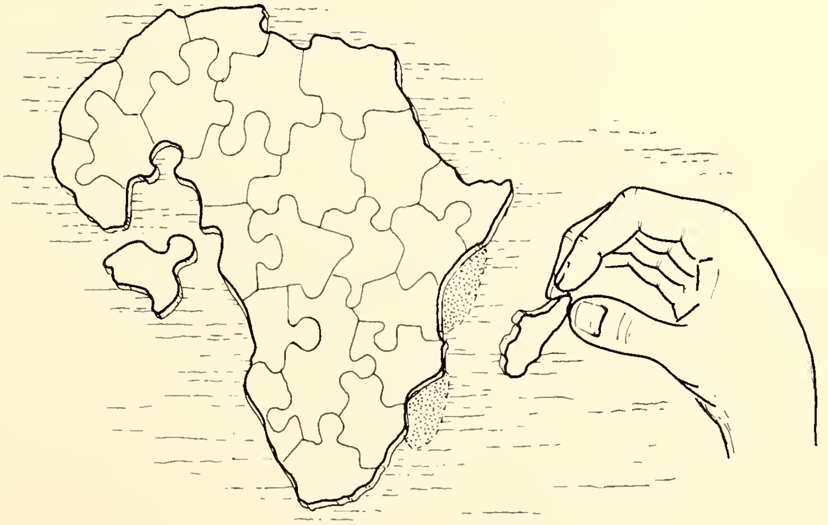
Wegener erred in departing from

the iceberg analogy. He assumed that continents actively ploughed their way through the mantle like great ships at sea, using forces he called *Westwanderung* (westward drift) and *Polefluchtkraft* (pole fleeing force). These forces, although real, were shown to be negligibly small and served to discredit the continental drift concept for a few decades.

A Jigsaw Puzzle

The reconstruction of the ancient supercontinents envisioned by continental drifters is a jigsaw puzzle. The jigsaw puzzle player has two clues: matching the picture, using color, tone or graphics; or fitting, using the shape of the pieces. The continental drift puzzle has the same clues. The "picture" is sketched by the bedrock geology, the foldbelt trendlines, distribution of glacial formations (tillites), etc. But there are difficulties. The geological picture resembles an impressionistic painting. No two observers seem to agree whether or not any particular assembly is really pictorially in sharp focus. Also full rendering is hindered by the contiguous parts being submerged continental shelves which are zones of no picture information, or "white paper." Furthermore the proper pieces are the continental outlines as delineated by the 1000-fathom line rather than by the shoreline or the shelf edge. Our marine surveys are not sufficiently good as yet to delineate the position of this contour.

Following Wegener's lead, many drifters have fitted the continents together by forcing the fit, i.e., by taking



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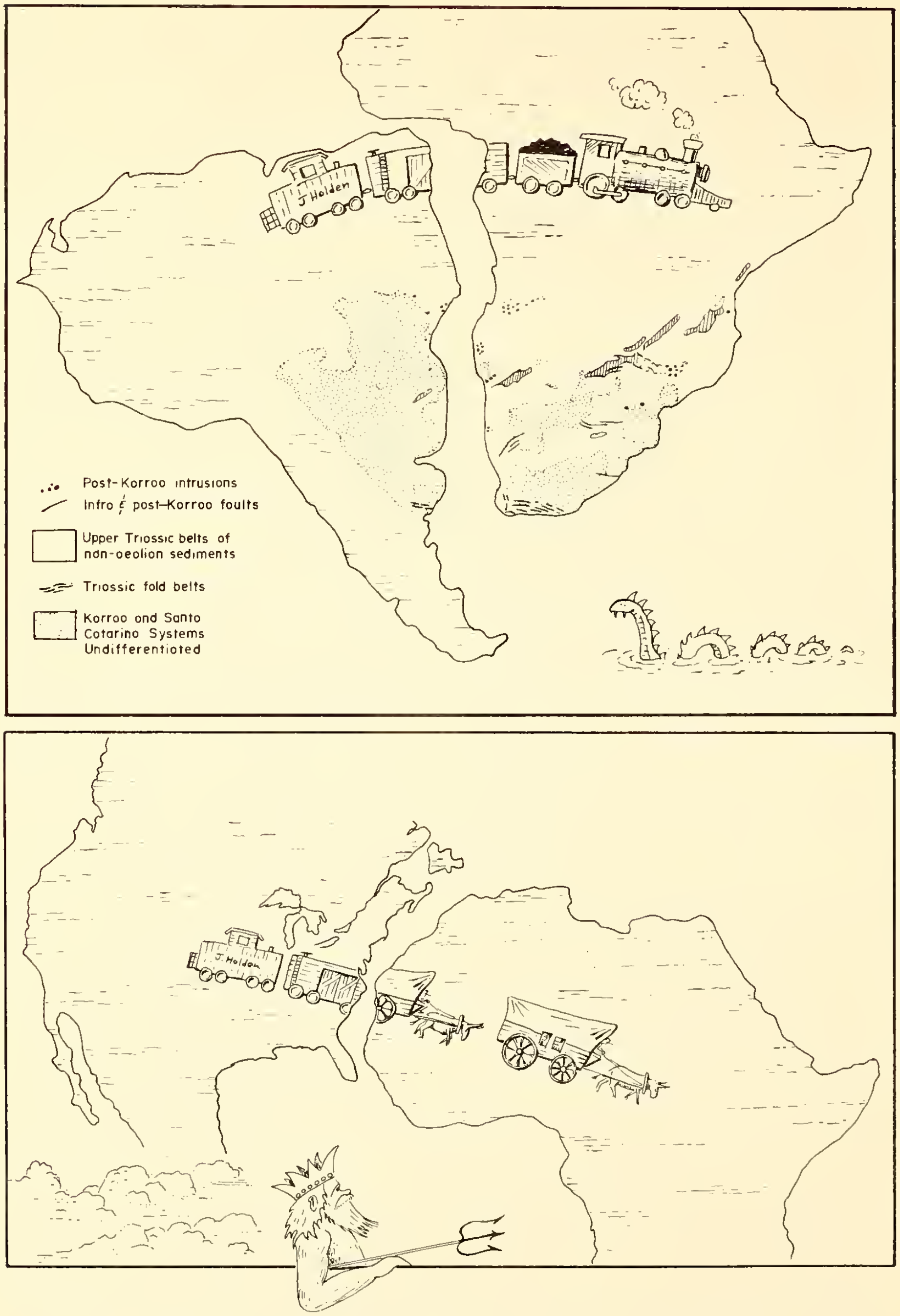

J. Holden
Post-Karroo intrusions
Intra & post-Karroo faults
Upper Triassic belts of non-aeolian sediments
Triassic fold belts
Karroo and Santa Catarina Systems Undifferentiated
J. Holden

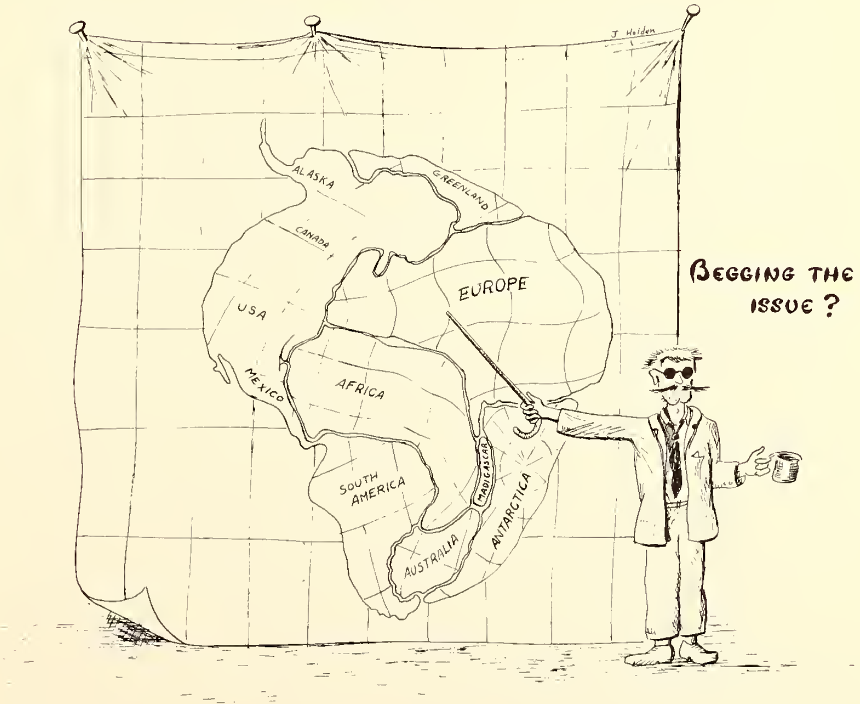
A JIGSAW PLAYER *has two clues. He may proceed by fitting the pieces by shape or by matching the design of the picture. Top: the pieces fit and the picture matches. Bottom: the pieces fit but the picture does not match.*

great liberties with the shapes of the pieces as though the continents were made of rubber. The reconstructions of former supercontinents are easy to make by such sketch-map methods, but are they meaningful? Using continental cutouts or templates for achieving fit on a globe is another favorite device of drifters. Unfortunately some of these have been done on a globe of 12-inch diameter or less. And one recent paper records the use of a 6-inch globe! Good "fits" are easy to achieve on a ping-pong-ball-sized globe.

Nonetheless, the case for the former existence of the southern hemisphere supercontinent of Gondwana, at least, is particularly strong. Attempting its reconstruction is a fascinating jigsaw puzzle—a game for the Gods, as some of the pieces are missing.

Tibetan Plateau: Two Continents Thick

India is universally recognized by drifters as a part of Gondwana, although it is physically attached to Asia. Geologists agree that the rocks of India are wholly unlike those of Asia. India's present position is ascribed to its having impinged against the underbelly of Asia on its journey north, forcing up the Himalaya Mountains and the Tibetan Plateau in the process. This may seem too much to believe, but it is actually reasonable. Tibet is 14,000 feet high, or equivalent to the relief of a continental slope. Looking north at



Following wegener's lead, *many drifters have made forced reconstruction by considering the continents as pliable as rubber . . . but are such fits meaningful?*

Good fits are easy *to achieve on a ping-pong-ball-sized globe.*

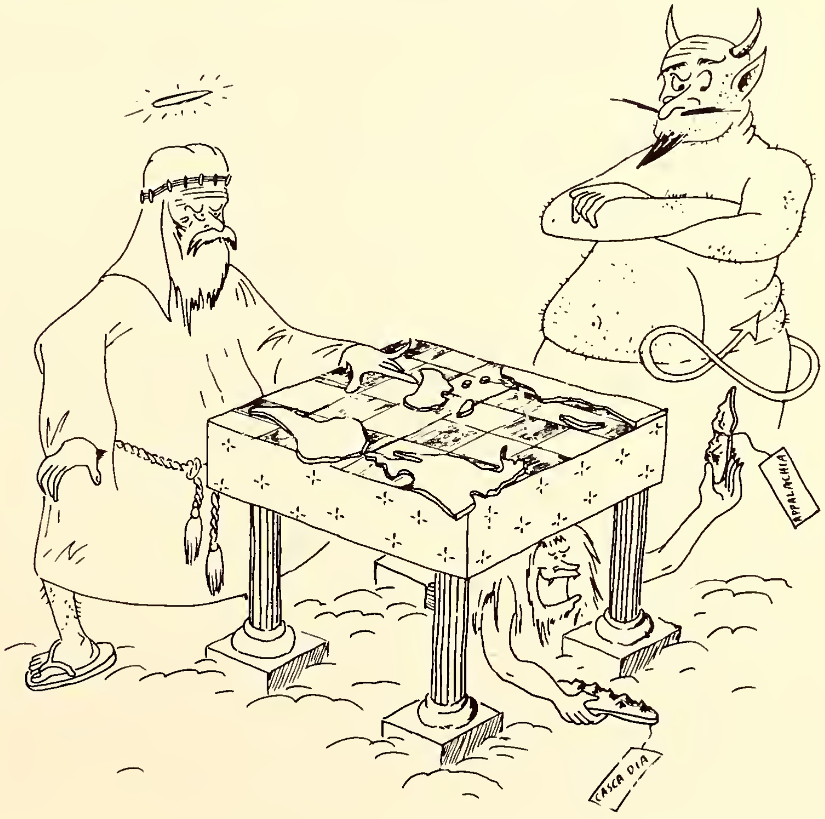
the Himalayan rampart from the resort city of Darjeeling, one sees the *only* land scarp in the world as grand as the continental slopes which surround all continents. The reason is precisely the same—the Indian continental plate has underridden the Asian plate, producing a double continent 70 km thick. Since continents float isostatically (i.e., are floating hydrostatically), the Tibetan Plateau is two continents high relative to the deep-ocean floor and one continent high relative to the land surface of India.

Almost Perfect Fit

Of course, the fitting of South America into Africa is a straightforward proposition. The parallelism of these opposing shorelines across the South Atlantic has been an inspiration to all drifters since the time of Wegener. He claimed that the geologic record could be read between South America and Africa as well as if those continents were pieces of a torn sheet of newspaper—a bit of an overstatement. The sketch maps of drift invariably show this fit but it apparently was thought to be only approximate. Only recently have geologists made the transposition with cartographic precision and, surprisingly, discovered that it dovetails beyond even the fondest hopes of the drift enthusiasts. Not only does the bulge of South America fit into the bight of Africa but the major bumps fit as well, and to some extent so do the bumps on the bumps. Some overlaps and gaps remain, but considering the vicissitudes of geologic history, the fit is too remarkable to be fortuitous. It must mean that these two continents were once juxtaposed. Our maps show a great ocean between Africa and South America, but geologically these two continents should be contiguous and conterminous.

Walter Sproll and I have recently obtained two other rather good Gondwana fits using precise and computerized methods. One of these places India, including Ceylon, against western Australia. Another wraps the south coast of Australia around Antarctica from the region of the Ross Sea westward. Many problems remain, however, before entire Gondwana can be pieced together using strict morphologic criteria. And we must stick to the rules, too, for the continental jigsaw game is not without constraints. It is not cricket, for example, to play continental leapfrog, although one South African geologist alleges that some jump-fits are as good as any of

CONTINENTAL DRIFT *is a game for the Gods as some of the pieces are still missing.*



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INDIA
THE ONLY WAY TO GO...

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those usually promoted by drifters.

The Mesozoic Break-Up

My tentative speculation as to how the continents dispersed would begin with the breakup and dispersal of the two supercontinents Laurasia and Gondwana commencing late in the Jurassic Period, in the middle of the age of dinosaurs, about 150 million years ago. Most likely this was a unique event in earth history. Certainly the continents have not been repeatedly fragmented through geologic time. There clearly had been a long period of geologic calm before this abrupt dispersal. In the northern hemisphere, North America swung away from Eurasia, rotating on a hinge point in southeastern Alaska. Previously Canada had been tied to Europe, and the eastern United States faced an Atlantic Ocean differently configured than now.

The southern continents were probably clustered together to form Gondwana and centered in the mid-Indian Ocean. An X-shaped rift opened up which dispersed India, South America-Africa, Antarctica, and Australia to the four directions of the compass. Sometime later, South America split off from Africa and moved still farther westward. The main stage of this scattering of crustal pieces was largely

GONDWANA
TIMES
SOUTH AMERICA
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AFRICA WOULD RATHER DRIFT THAN FIGHT
NO NO NEVER
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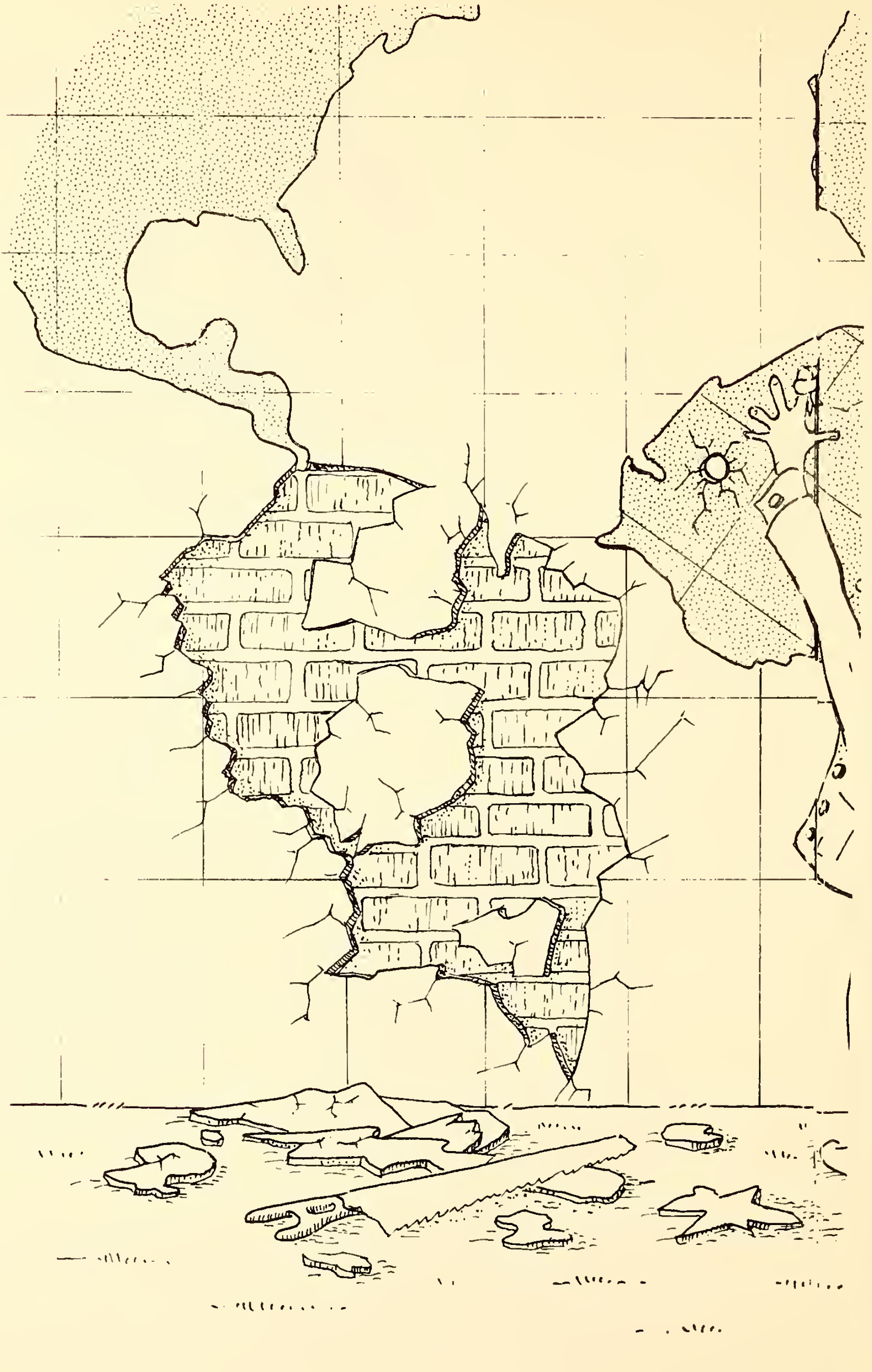
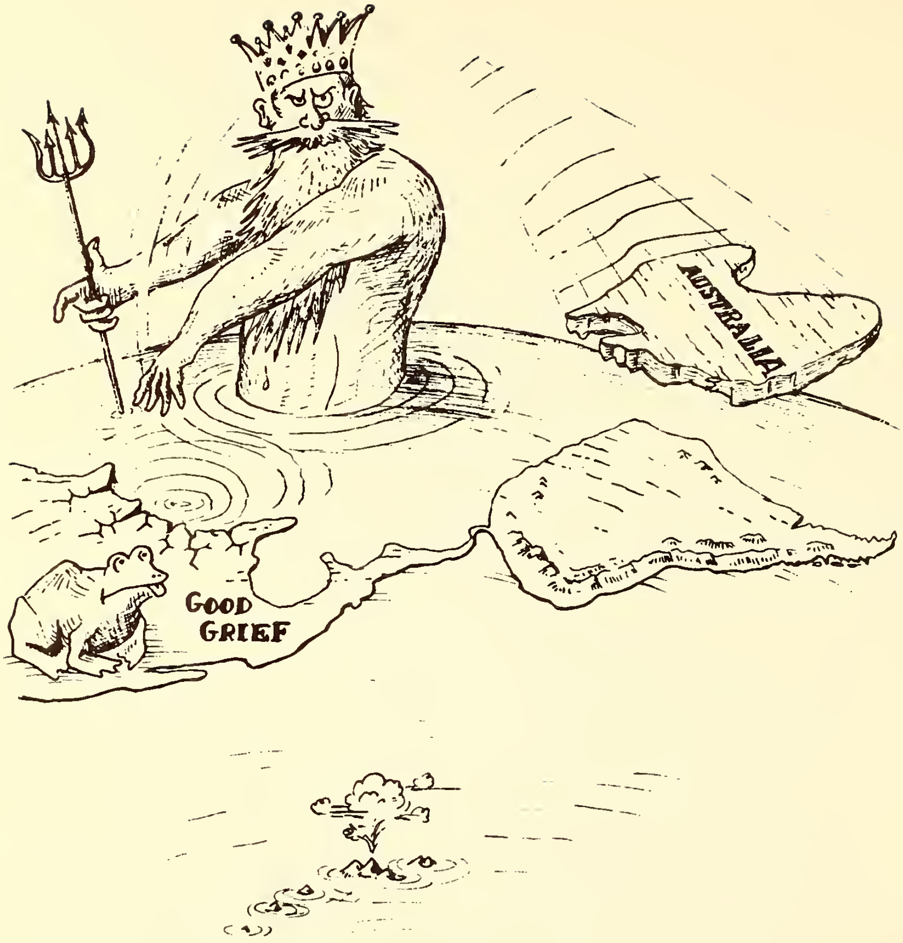


OUR MAPS SHOW *a great ocean between Africa and South America but because of geological features and similarities these two continents should be contiguous and conterminous.*



THE CONTINENTAL DRIFT JIGSAW GAME *is not without constraints. It is not cricket, for example, to play continental leapfrog, although one South African geologist claims that some jump fits are as good as any of those usually promoted by drifters.*

over by the end of the Mesozoic Era, 60 million years ago.

Drift was initiated by the earth's mantle becoming suddenly "restless" and undergoing some sort of overturn in response to having built up too much internal heat by the slow decay of radioactive uranium, thorium and potassium. The great world-wide sinuous mid-ocean ridge with its central rift was the scar resulting from this. But this seems only approximately true; for the continents cannot be fitted back into this linear birth scar. The mid-ocean rift virtually encircles Africa (except in the Mediterranean) forming a "ghost of Africa," an enlarged outline of the continent, which apparently expanded outward in all directions.

The effect of continental breakup can thus be seen around Africa, for it was the heartland of Gondwana. In pre-drift time, only the north coast of Africa now facing the Mediterranean was open to the world ocean. The rifting presumably began along the northeast coastline of India, detaching India and then Madagascar. The splitting then extended southward, along Mozambique to Cape Horn, detaching Antartica. Next the rifting turned northward up the Atlantic side of Africa, separating South America. Thus nearly all of the coastline of Africa was blocked out and a modern shoreline established 150-100 million years ago (in late-Jurassic to mid-Cretaceous time), the heroic period of continental drift.

The post-Mesozoic period of quiescence was temporary, ending about 15 million years ago. It now appears that the unstable ends of the snakelike mid-ocean rift have shifted. One tail, formerly in the central Pacific, has swung under western North America opening up the Gulf of California and arching the entire western limb of our continent. Another tail, in the Indian Ocean, has circled into the Red Sea and down through eastern Africa,

IN AUSTRALIA, *the belief is popular that the continents have been dispersed by an expanding earth.*

creating the African Rift Valleys. The Arabian block has recently been translated 200 km and rotated counterclockwise 8°.

A Final Comment

In Australia the belief in an expanding earth is a popular explanation for the apparent continental dispersion. It is proposed that the ocean basins alone have essentially doubled their surface area in the past 150 million years while the continents have remained unchanged in size and shape. I can hardly accept this interpretation, for such an expansion would have resulted in a great lowering of sea level. A fundamental relationship exists between the depth of the sea and the thickness of the continental plate so that any drawdown of sea level would have caused catastrophic denudation of the continental areas. The resulting erosional havoc to the continents would be clearly visible in the geologic record, but it is not. The continents would have been stripped of their Paleozoic veneers of marine sediments, but they have not.

Although controversy continues unabated, the theory of continental drift bolstered by the new evidence of paleomagnetism, after a period of rejection, is now very much alive. Project Mohole is dead, but a new program jointly sponsored by a consortium of oceanographic institutions for drilling many shallow holes in the deep sea is now in the offing. When the results of this effort are finally assessed, I am quite sure that we will find that our shifty continents are, and have been, on the move.